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OTH RADAR SURVEILLANCE AT WARF DURING THE LRAPP CHURCH OPAL EXERCISE (U)

By: JAMES R. BARNUM

Prepared for:

OFFICE OF NAVAL RESEARCH
FIELD PROJECTS PROGRAMS, CODE 461(FP)
ARLINGTON, VIRGINIA 22217

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STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

Technical Report 39 November 1976

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SRI Project 4062

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(S) In September 1975, the Wide Aperture Research Facility (WARF) Over-the-Horizon Radar (OTHR) performed shipping surveillance as part of the Long-Range Acoustic Propagation Project (LRAPP) exercise Church Opal. The purpose of the OTHR experiment was to help determine the density and distribution of ships in three Pacific Ocean areas, each 5° by 5° square. The noise emitted by ships sometimes reduces the sensitivity of underwater acoustic systems.

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(S) Over a period of five days, 26 separate ships were detected and tracked at WARF. An ocean area of approximately 250,000 km^2 was searched eight times each day. The largest number of ships detected was nine, and the smallest was two, on any given day. Ship radial speeds ranged between 11 and 23 knots, and estimated ship lengths varied between 300 and 650 ft or more. OTHR and P3 ship density results were compared on the last day of WARF operation, and the agreement was good. By comparison, however, the correlation of the positions of individual ships reported by P3 and OTH radars was relatively poor. Both high probability OTHR detections and P3 detections were apparently not seen by the opposite sensor.

(S) Church Opal was the second of three recent formal tests of the OTHR ship surveillance capability at WARF. It was the first time that any OTHR had routinely searched large ocean areas for surface shipping. The wide-area ship surveillance performed by OTHR in this experiment demonstrated utility for this and similar ocean surveillance applications. Recommendations for future work are discussed.

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(U) The personnel at the Remote Measurements Laboratory were pleased by the invitation from LRAPP to participate in Church Opal. We had frequent association with Dr. Louis Solomon at Planning Systems Incorporated, who was responsible for correlating the SRI results with in-situ observations.

(U) This work was sponsored by the Office of Naval Research, Code 102 (LRAPP) and Code 464, under Contract N00014-75-C-0930.

I INTRODUCTION (U)

(S) High-resolution, long-range, remote surveillance of surface shipping has been under continuous development at SRI's Wide Aperture Research Facility (WARF) Over-the-Horizon Radar (OTHR) since 1969. Major technological advancements began in 1971, with the combined use of WARF's high spatial resolution and Doppler signal processing. Resolutions as small as 13 km in cross-range by 750 m in range have been used successfully. Automatic ship detection on five contiguous antenna beams, tailored uniquely for ship detection in sea clutter, was soon developed. This processing capability gave WARF a real-time ship surveillance capability that proved highly suitable for demonstration and interaction with other U.S. Fleet ocean surveillance resources.

(S) Informal experiments with the Fleet, from 1971 to the present, have helped to establish and improve the basic WARF operational capability for the tracking of single ships under a large variety of circumstances.

(S) Formal demonstrations of OTHR ship-surveillance utility began in February 1975 with WARF participation in the Fleet exercise Outlaw Hawk. Fleet ships, including destroyers, and several targets of opportunity were tracked both day and night and the USS Kitty Hawk task group was notified of approaching ships. It was determined that OTHR had utility as an active remote sensor for multi-source correlation in ocean surveillance (Refs. 1 and 2).*

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* (U) References are listed at the end of the report.

(S) Participation in the Church Opal exercise was considered to be WARF's second formal test of the utility of OTHR ship surveillance. Here, however, the emphasis was directed toward relatively large area surveillance for targets of opportunity. It is the purpose of this report to describe these results and to discuss the future operational OTHR capability that can be extrapolated from Church Opal.

A. Purpose of Experiment (U)

(C) Church Opal was one of a series of exercises conducted by the Long Range Acoustic Propagation Project (LRAPP). Its purpose was to acquire environmental acoustic data required for antisubmarine warfare (ASW) program decisions, as described in Refs. 3 and 4.

(S) Ship surveillance by OTHR was used in Church Opal to help determine the distribution of surface shipping. Noise emitted from ships can sometimes significantly reduce the sensitivity of underwater acoustic sensors. Prior work conducted by Solomon and others (Refs. 5 and 6) had led to models for the average density of ships in the Pacific Ocean, and these models are being refined. It is believed that real-time surface radar measurements are necessary for these refinements. P3 aircraft have previously been used for this purpose and were also included in the Church Opal exercise. The OTHR and P3 data were directly compared on one of the days of WARF operation.

(S) The technical objectives for shipping surveillance in Church Opal were the following (Ref. 4):

- Determine the nearby shipping distribution concurrent with the LAMBDA and DELTA (towed arrays) directionality measurements.
- Determine ships on LAMBDA beams during beam noise threshold measurements.

(S)

- Evaluate the OTHR measurements of shipping distribution (insofar as possible) using simultaneous P3 aircraft surveillance.

(S) As part of these objectives, three OTHR surveillance areas were chosen by LRAPP within the WARF coverage, as shown in Figure 1. Each was 5° by 5° square, in latitude and longitude. The dates of WARF operation associated with each area are shown in Table 1.

Table 1

(U) SURVEILLANCE SCHEDULE (U)

Area	Day
1	9-10-75
3	9-11-75
3	9-12-75
2	9-13-75
2	9-14-75

B. <u>WARF Research Objectives</u> (U)

(S) Church Opal required much greater area coverage than previous WARF ship detection experiments, and far less time was spent tracking individual ships. Indeed, LRAPP wished only to receive ship density results, not tracks. A major objective was to learn what scanning strategies and tracking methods (for target verification purposes) were most appropriate for this application.

(C) Analysis of radar parameter tradeoffs--basically area resolution versus target revisit time--led to the requirement for no less than 7.5 km range resolution to provide coverage of the 5°-by-5° areas at least eight times each day. This resolution is a factor of 10 larger

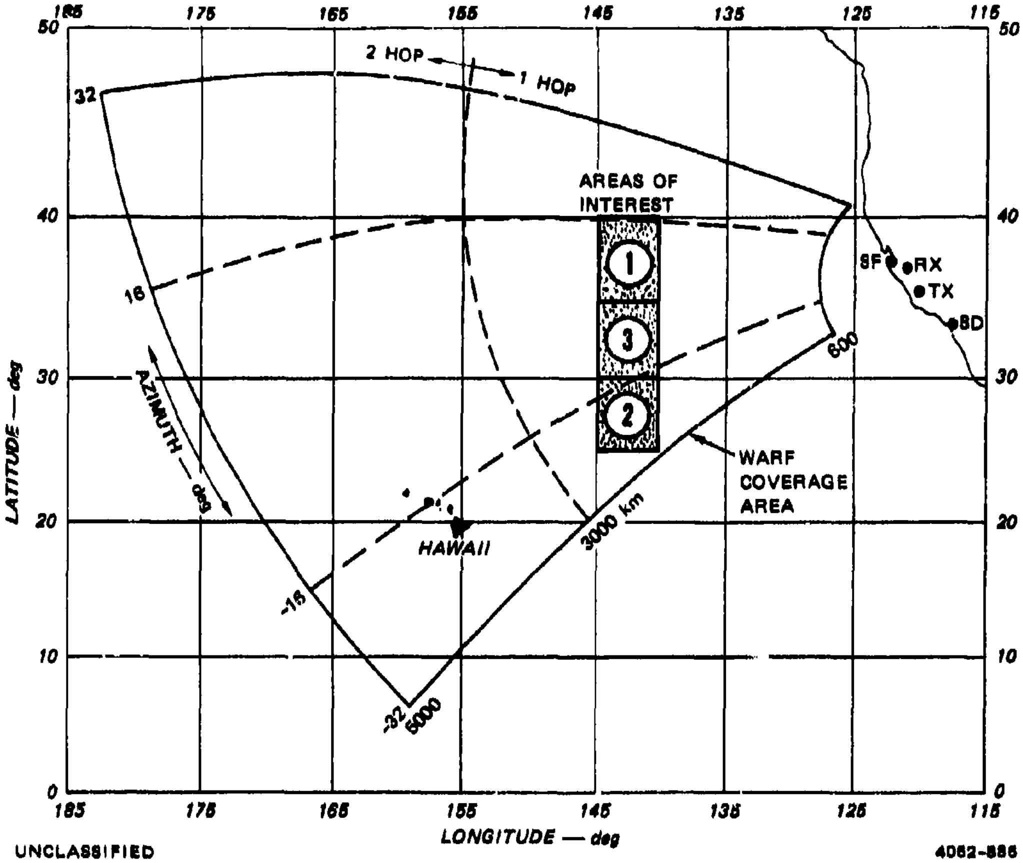

FIGURE 1 WARF OTHR SURVEILLANCE AREAS FOR CHURCH OPAL (U)

(C)

than can often be achieved, and is a factor of 2.5 larger than the value of 3 km normally used. A sacrifice in sensitivity against sea clutter thereby resulted, but the area coverage rate was increased to the desired amount (as described in Section II and the Appendix of this report). Another major objective was to determine the general suitability of these parameters for wide area surveillance.

C. Research Background (U)

(C) Summaries of key results in WARF OTHR ship surveillance through March 1975 were presented in Ref. 7 and in the report of WARF results in the Fleet Exercise Outlaw Hawk (Ref. 2).

(S) By the time of Church Opal, a great many ships had been tracked at WARF, with sizes ranging from 350-ft destroyers to 1100-ft aircraft carriers. Ship radial speeds had ranged from 0 to 5 knots and from 9 to 26 knots; ships with speeds between 5 and 9 knots remained difficult to detect in the strong resonant sea clutter echoes at Doppler frequencies equivalent to these speeds. Automatic detection and tracking had been performed both day and night in real time (Ref. 2). The probability of detection (P_D) for ships was well understood, which was useful for surveillance planning. Key operational factors had been the use of high spatial resolution, frequent target revisits, careful propagation analysis, and efficient radar frequency management.

(C) Development of a second-generation on-line automatic tracker was undertaken prior to Church Opal, but was not complete at the time of the exercise. The older tracker was modified for real-time use (Ref. 2), but was far too slow for use in the Church Opal wide-area search-and-verify application. This tracker (Refs. 2 and 8) has been used extensively after experiments to review digitally recorded data and to form highly accurate ship tracks. The real-time tracking approach in Church Opal was to flag ship detections and perform casual verification in real time. Thorough detection verification and track formation were performed after the experiment.

D. Summary of Results (U)

(C) Ocean areas about 250,000 km^2 in size, or approximately 5° by 5° square, were surveyed eight times a day. Well over half of the 500

(C)

to 600 daily radar dwells were usable for ship detection. Unusable radar dwells were produced by poor ionospheric propagation or by the reception of meteor echoes.

(S) A total of 23 good tracks, containing a total of 26 ships (two ships per track in three cases), were delivered to LRAPP analysts at Planning Systems, Inc. (PSI) after the experiment (Ref. 9). Ship radial speeds ranged from 11 to 23 knots, while estimated true ship speeds ranged from 14 to 25 knots. Both inbound and outbound ships were tracked. From the average measured radar cross section (RCS), ship sizes appeared to range from about 300 to 650 ft and possibly larger.

(S) Table 2 lists the number of ships detected and the number of tracks formed during the five days of operation. On 10 September it is believed that one track had two ships closely spaced, and on 14 September two tracks appear to have had two ships in a group. Thus, the number of ships detected exceeds the number of OTHR tracks formed on those two days.

(S) In the preliminary data analysis (Ref. 9, Appendix E), somewhat arbitrary confidence levels of 90%, 50%, and 25% were originally assigned to a total of 32 tracks that, together, contained 35 ships. A track with enough detections and sufficient elapsed track time to guarantee good accuracy in course and speed was assigned the "90%-confidence" level. The 50% tracks, however, contained rather few detections. In this preliminary analysis (Ref. 9), we stated that false echoes had (possibly) produced something less than half of these 50% tracks. It is now believed that none of these tracks is false. The echoes from each 50% track were strong and consistent with the movement of ships. The 25% tracks (nine in number) have been discarded. Each contained only two or three detections, which are not considered sufficient for ship target verification with an OTH radar.

Table 2

(U) SHIP DETECTION RESULTS (U)

Day	Operating Time (Z)	Number of Tracks Formed	Number of Ships Detected
9-10-75	1723-0239	4	5
9-11-75	1727-0223	4	4
9-12-75	1723-0212	2	2
9-13-75	1634-0238	6	6
9-14-75	1636-0215	7*	9
Total		23	26

(S) The PSI analysis has indicated good agreement between WARF OTHR ship density measurements and those from P3 radar surveillance. The measurements also fit the PSI statistical model for shipping density (Ref. 9). By comparison, however, the correlation of the positions of individual ships reported by P3 and OTH radars was relatively poor. Both high probability (well verified) OTHR detections and P3 detections (of unknown probability) were apparently not seen by the opposite sensor.

(S) Future ship surveillance operations over relatively wide ocean areas should devote more effort to the real-time verification and correlation of ship detections. This procedure would insure high accuracy in measurement of target course and speed, and would increase the accuracy for extrapolation of ship tracks to other times of day. Present WARF resources now include rapid automatic ship tracking for this purpose.

(S)

Higher radar resolution--hence, greater sensitivity--could be achieved with smaller surveillance areas using WARF. A stationary-fence type of scanning strategy could be used to detect ships under normal east-west transit. For example, detection results from a single fence scanned over a 10-hour period could be used to calculate ship density over an effectively larger area, depending on ship speed.

(S) A modest operational prototype OTH radar would not be similarly limited. It would include the sensitivity achievable at WARF with higher resolution and longer data integration, but would have an area coverage rate in excess of 50 times that of WARF. Compared to the parameters used for Church Opal, this radar would develop an 11-dB greater sensitivity against sea clutter, and could cover a 5°-by-5° area eight times in only 1 hour or less.

E. Organization of Report (U)

(S) Section II of this report describes the choice of radar surveillance parameters and the area coverage for Church Opal. Section III describes the ship tracking procedure and illustrates the tracks obtained on each of the five days of operation. Section IV concludes the main text of the report with suggestions for future experiments aimed at wide-area ship surveillance by OTHR.

(U) A more detailed discussion of the key tradeoffs in the choice of radar operating parameters for large-area surveillance is included in the Appendix. The capability of a modest prototype operational OTHR is described for comparison.

II SURVEILLANCE APPROACH AND AREA COVERAGE (U)

A. Surveillance Parameters (U)

(S) Limited processor capacity required careful selection of operating parameters in order to most effectively survey the 5°-by-5° areas. These areas are large by present WARF processing standards, due to the use of high spatial resolution necessary for ship detection. As explained in the Appendix, the operating and processing tradeoffs essentially fall into three categories:

- Target area revisit frequency
- Spatial resolution
- Integration time (both coherent and noncoherent).

(S) The intention was to use the full WARF receiving array to provide maximum azimuth resolution for clutter reduction and target positioning, and to perform automatic detection on five contiguous antenna beams simultaneously. It was determined subsequently that the best surveillance sensitivity could be obtained with WARF by:

- Scanning the area eight times for high probability of detection
- Using 7.5 km range resolution
- Using 12.8 seconds of coherent integration, followed by two noncoherent averages, for a net one-minute radar dwell.

This yields a loss in sensitivity of 7 dB compared to the use of 1.5 km range resolution, and an additional loss of 4 dB compared to the use of a 2-minute radar dwell with seven noncoherent averages. The realization of this 11 dB extra sensitivity, however, would have allowed efficient coverage of an ocean area only one-tenth the size of the Church Opal

(S)

areas, or about 1.5° by 1.5°. As shown in the Appendix, a modest operational OTHR would not be similarly limited.

(S) Nevertheless, it is clear that the radar sensitivity for Church Opal was sufficient to permit detection of ships approximately 400 ft in length and larger, operating at radial speeds in excess of about 10 knots or more, and smaller ships at slightly higher speeds.

B. Area Coverage (U)

(U) Summaries of the ocean areas surveyed and the times of operation on each day with good data are presented in Figures 2 through 6. The area corresponding to each radar dwell is outlined (approximately rectangular), but the number of exactly overlapping dwells cannot be discerned from the figures. Each dwell contained 105 individual (but somewhat overlapping) resolution cells that were recorded simultaneously. In some instances, many dwells were devoted to the verification of ship targets by concentrated sampling of single areas. Well over half of the 500 to 600 daily radar dwells were usable. The unusable radar dwells contained meteor echoes which often camouflage ships, insufficient signal strength (necessitating radar frequency changes), or unusually spread sea clutter due to multipath or disturbed ionospheric conditions.

(U) Contiguous, constant-range fence scans were employed to search each 5°-by-5° square, and 15° of radar azimuth were required for each scan. This surveillance technique is one of the most efficient for OTHR operations, since the optimum radio frequency for ship detection is often nearly constant over this azimuth extent at a constant range. In contrast, new frequencies must usually be found when the radar range is changed by 300 km or more. It will be noted from Figures 2 through 6

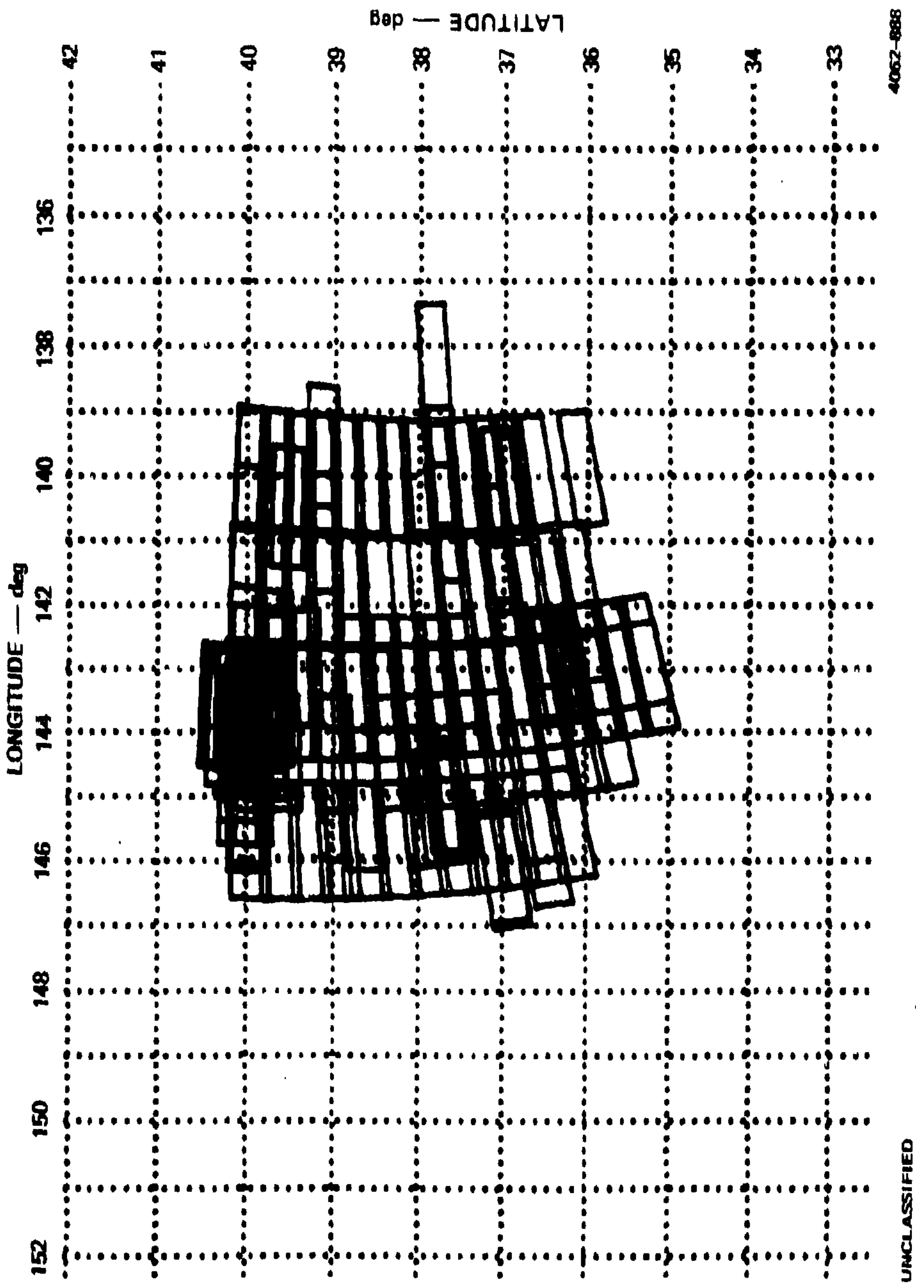

FIGURE 2 WARF OTHR COVERAGE ON 10 SEPTEMBER 1975. Usable data were recorded between the hours of 1723Z and 0240Z. Each coverage rectangle contains 105 radar resolution cells. (U)

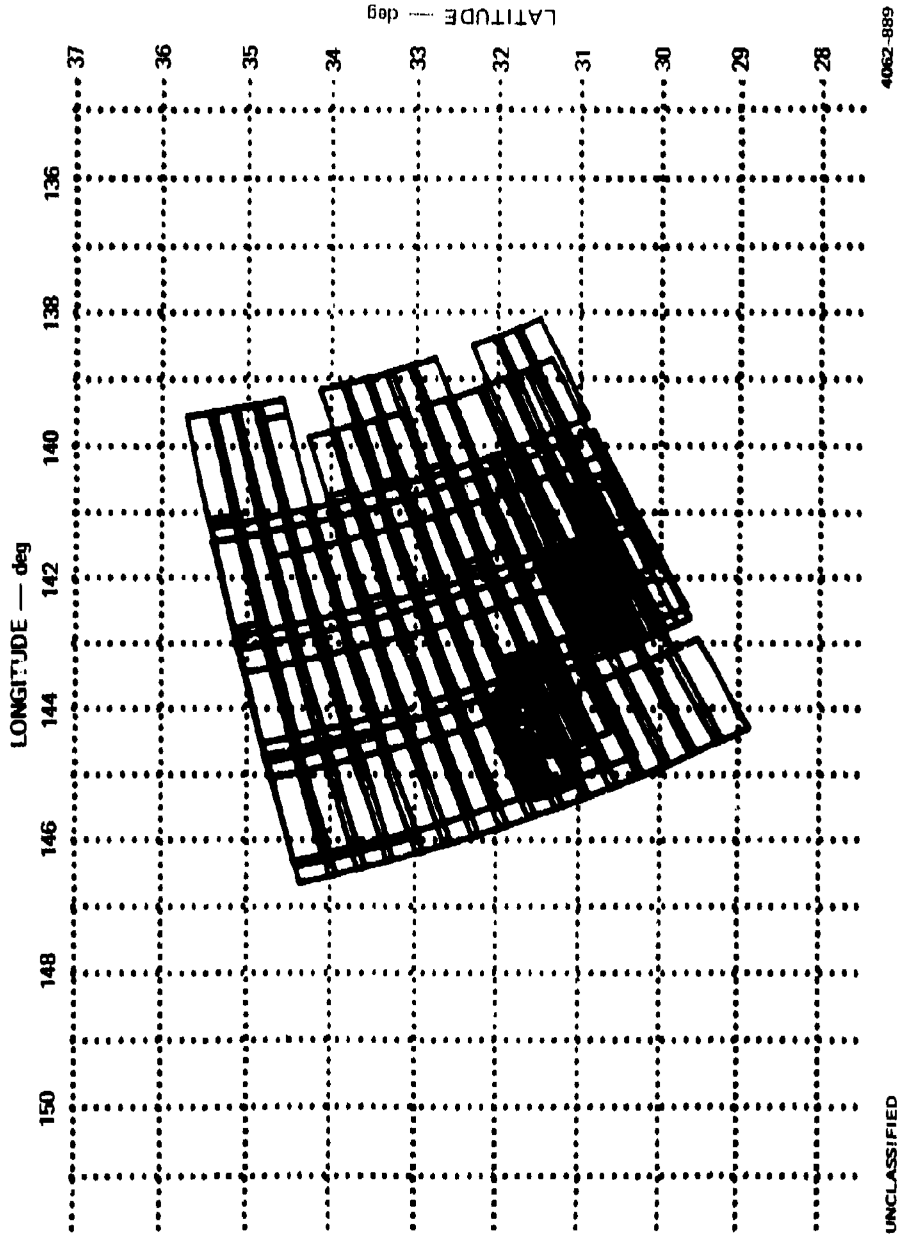

FIGURE 3 WARF OTHR COVERAGE ON 11 SEPTEMBER 1975 BETWEEN 1727Z AND 0224Z (U)

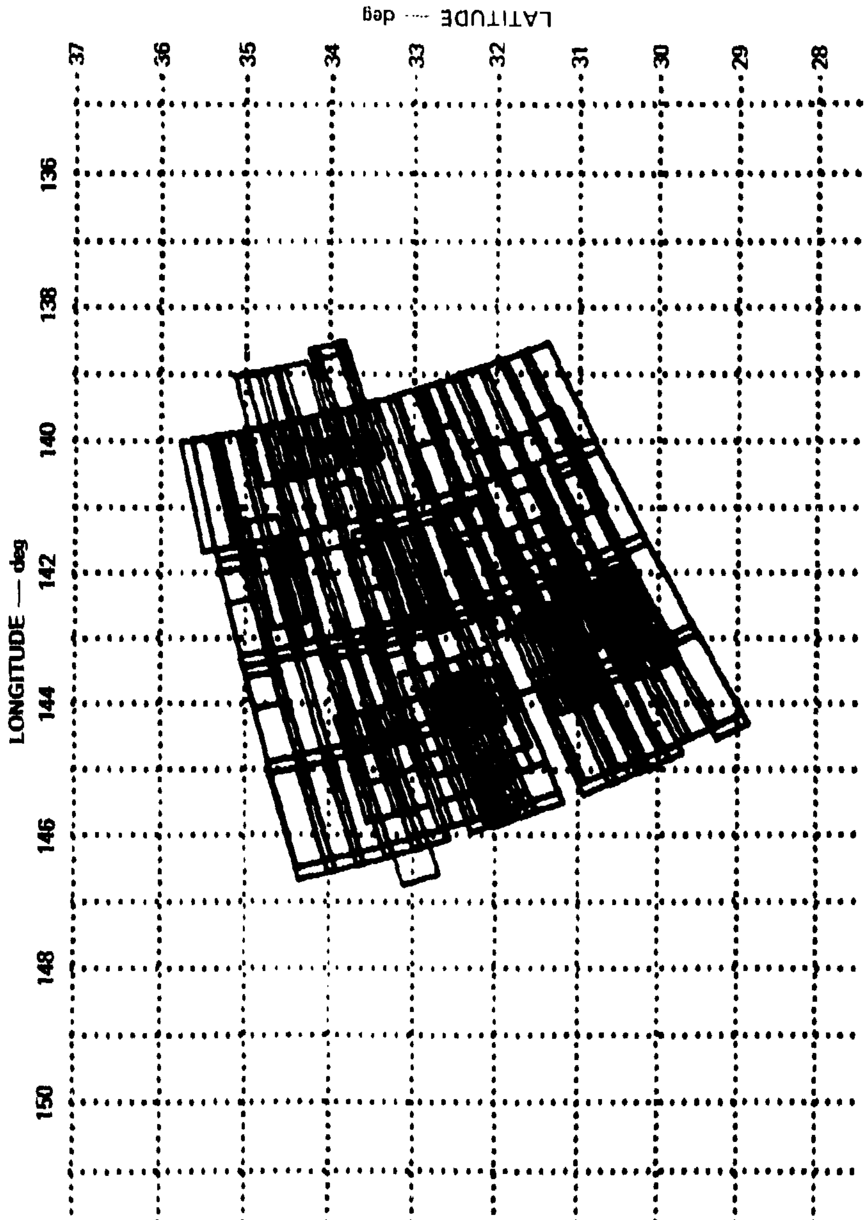

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FIGURE 4 WARF OTHR COVERAGE ON 12 SEPTEMBER 1975 BETWEEN 1723Z AND 0213Z (U)

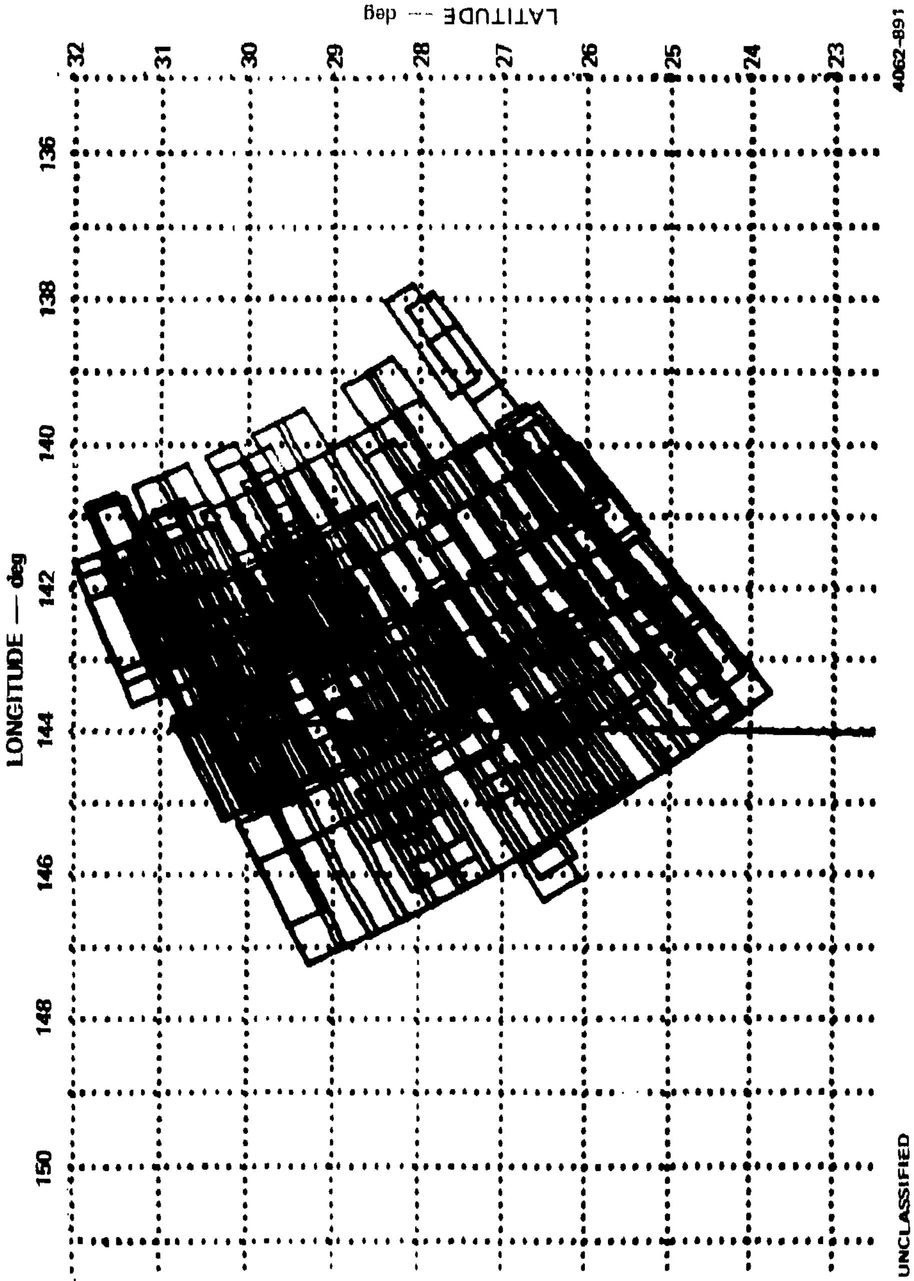

FIGURE 5 WARF OTHR COVERAGE ON 13 SEPTEMBER 1975 BETWEEN 1634Z AND 0238Z (U)

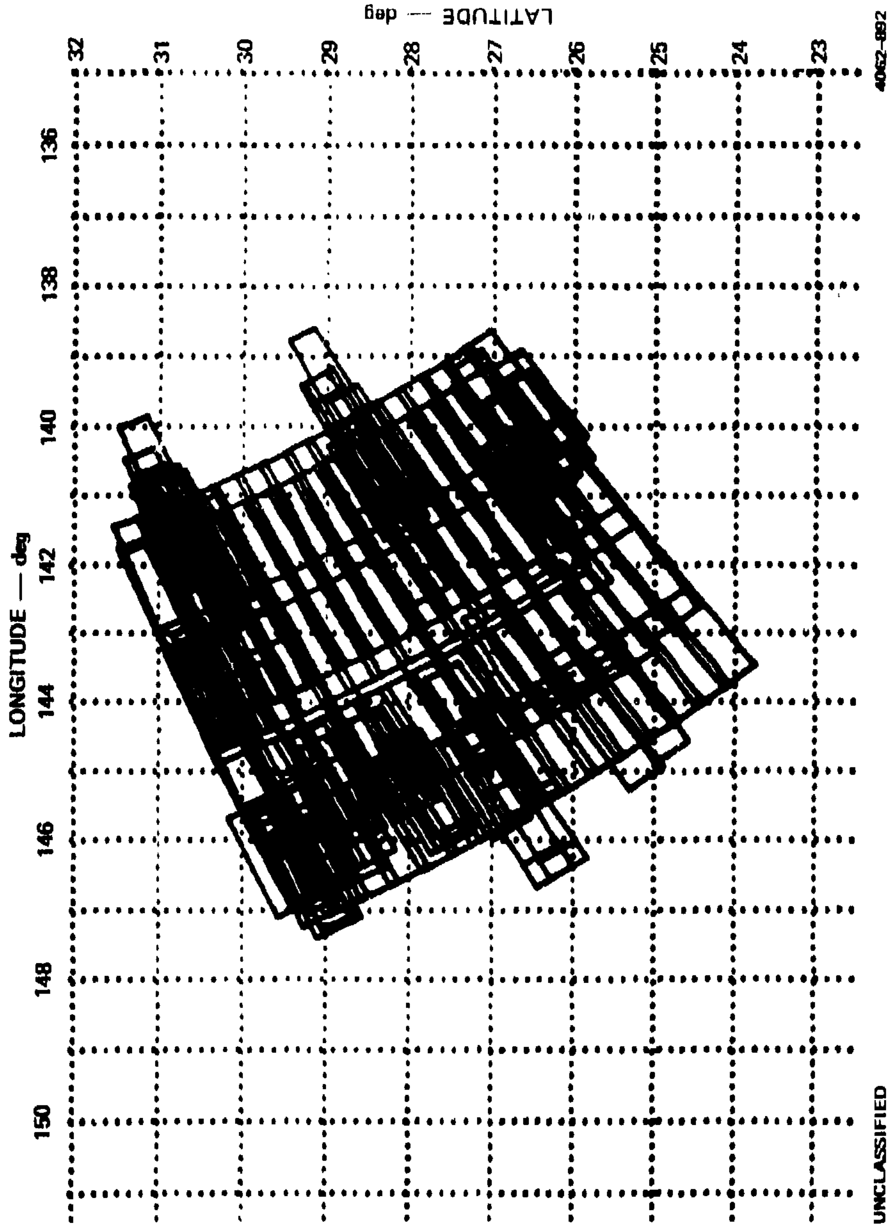

FIGURE 6 WARF OTHR COVERAGE ON 14 SEPTEMBER 1975 BETWEEN 1637Z AND 0216Z (U)

(U)

that the radar coverage areas are misaligned with the 5°-by-5° areas, since lines of constant range and azimuth are not parallel to geographical coordinates.

(S) A total of about 4,000 resolution cells were sampled on the average eight times each day for the purpose of detecting ships. Each resolution cell measured 7.5 km in radar range depth and nominally 19 km in azimuth width (at the center of coverage) or about 140 km^2 per cell (average). Adjacent cells overlapped about 45%, and every fifth cell was duplicated (see Appendix). The total ocean area surveyed per day thus measured about 250,000 km^2 which is equivalent to a geographical area approximately equal to 5° by 5°.

III SHIP TRACKING RESULTS (U)

A. Tracking Procedure (U)

(U) A single fence scan through an area required 15 minutes to complete. Detections recorded during a scan were logged, and the detection areas were revisited following scan completion. Verification of possible targets lasted 5 to 30 minutes, after which new scans were programmed.

(C) Detections were thoroughly sorted after the experiment to verify detection correlation. Each target detection list was then used to form a track, basically as described in Ref. 8, but with some simplification because most tracks were relatively short. Briefly, the track formation by digital computer proceeded as follows:

- The target time delay was plotted versus time. The average radial speed was used to calculate a linear time-delay regression, and this line was fitted to the measured time delay on a least-squares basis.
- A straightforward first-order least-squares regression was calculated for the target azimuth history.
- The regression curves for time delay and azimuth and the average virtual ionospheric height were used to calculate target latitude and longitude (Ref. 10, Appendix B).

The following sections describe these tracking results.

B. Tracker Example (U)

(C) An example of the tracker output is shown in Figure 7. Data that are directly pertinent to the track are printed beneath the figure as follows:

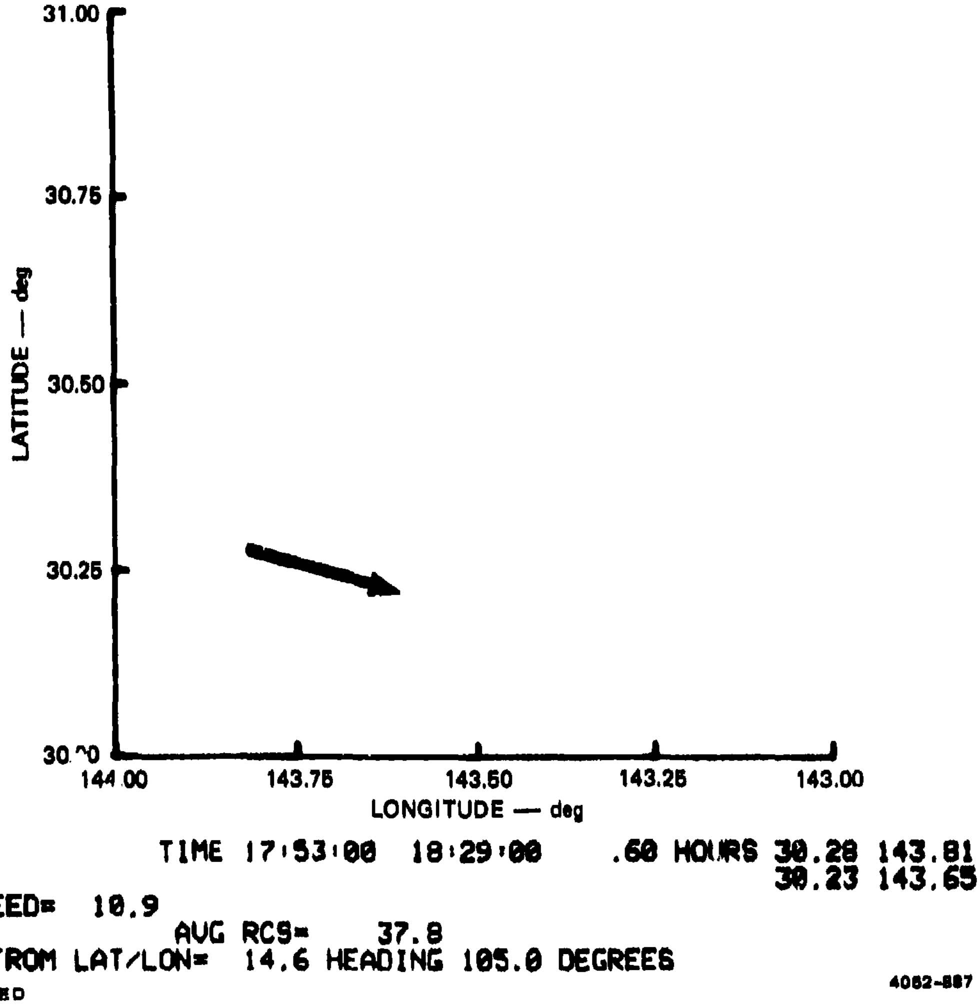

FIGURE 7 EXAMPLE SHIP TRACK DISPLAY AFTER AUTOMATIC ANALYSIS OF SELECTED DETECTIONS RECORDED ON DIGITAL TAPE DURING CHURCH OPAL (C)

(C)

- The first and second lines give the begin and end times (Zulu) of the track, the track duration, and the begin and end positions (in decimal degrees).
- The third line gives the average observed radial speed (in knots).
- The fourth line gives the average estimated radar cross section (AVG RCS).

(C)

- The fifth line gives the calculated true speed (in knots) and course heading at the end of the track.

Less pertinent data printed beneath each track have been deleted from the example in Figure 7 for the sake of clarity.

(C) The accuracy of the track is determined by two factors:

- The estimate of the ionospheric height, which determines the position of the track as a whole. The track accuracy should be within 20 km.
- The length of the tracking time, during which fluctuation in target echo azimuth with time determines the accuracy of the course heading and true speed. On the short term, the equivalent cross-range error due to azimuth fluctuations is less than 20 km. As tracking progresses, a least-mean-squares estimate of the azimuth history is formed, which reduces the uncertainty. Most azimuth fluctuations do not exceed ±1/4° (and 10 km), and have a period of about 15 minutes, from which a good estimate of the mean value can be calculated.

C. Tracking Summary (U)

(C) Figures 8 through 12 illustrate the tracks of the ships listed in Table 2 for each day's operation. Outlines of the daily WARF coverages, from Figures 2 through 6, respectively, are overlayed on the 5°-by-5° squares nominally covered. Ship tracks constructed using either several detections, or relatively few detections, are noted in the figures. The tracks with only a few detections cannot be as reliably extrapolated to other times of day. The time of day at the beginning and end of each track is indicated. Times in the range of 0000Z to 0300Z actually apply to the following day as measured in universal time (Zulu). Tracks that have only a single time were formed over a very short period, and possess the course inaccuracies discussed above. In these cases, the

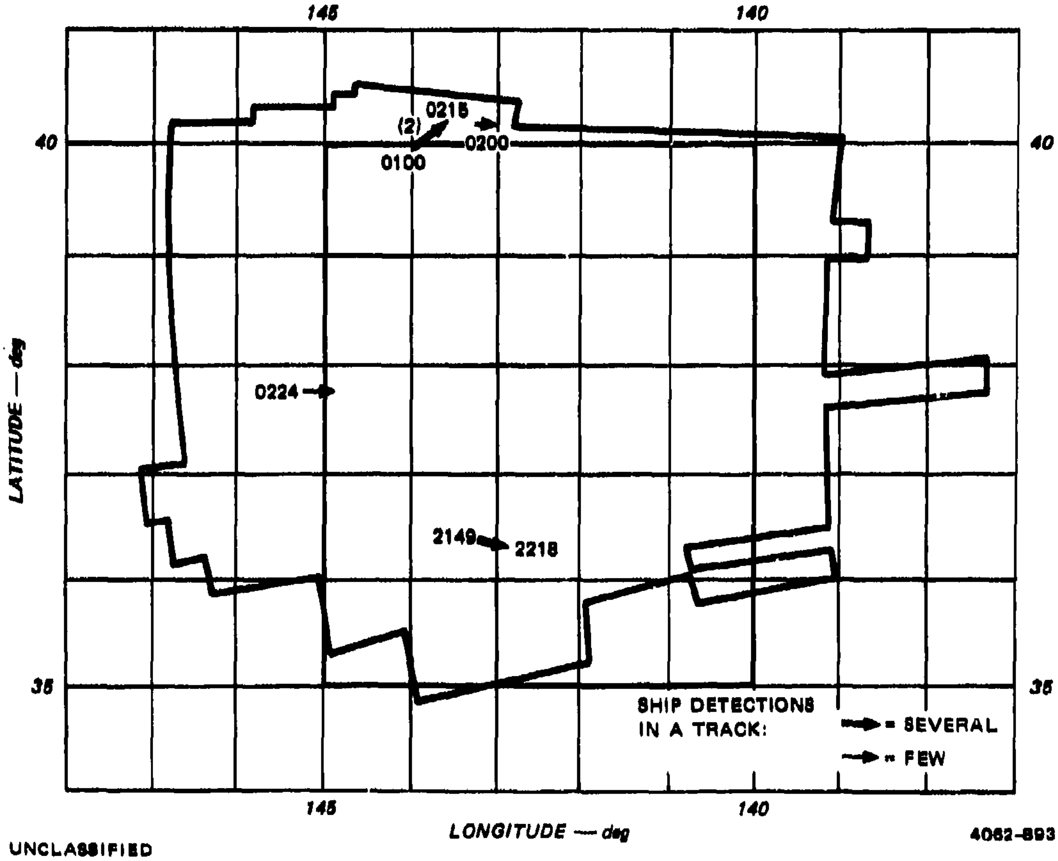

FIGURE 8 WARF OTHR SHIP TRACKS FOR 10 SEPTEMBER 1975 AND OUTLINE OF RADAR COVERAGE FROM FIGURE 2 (C)

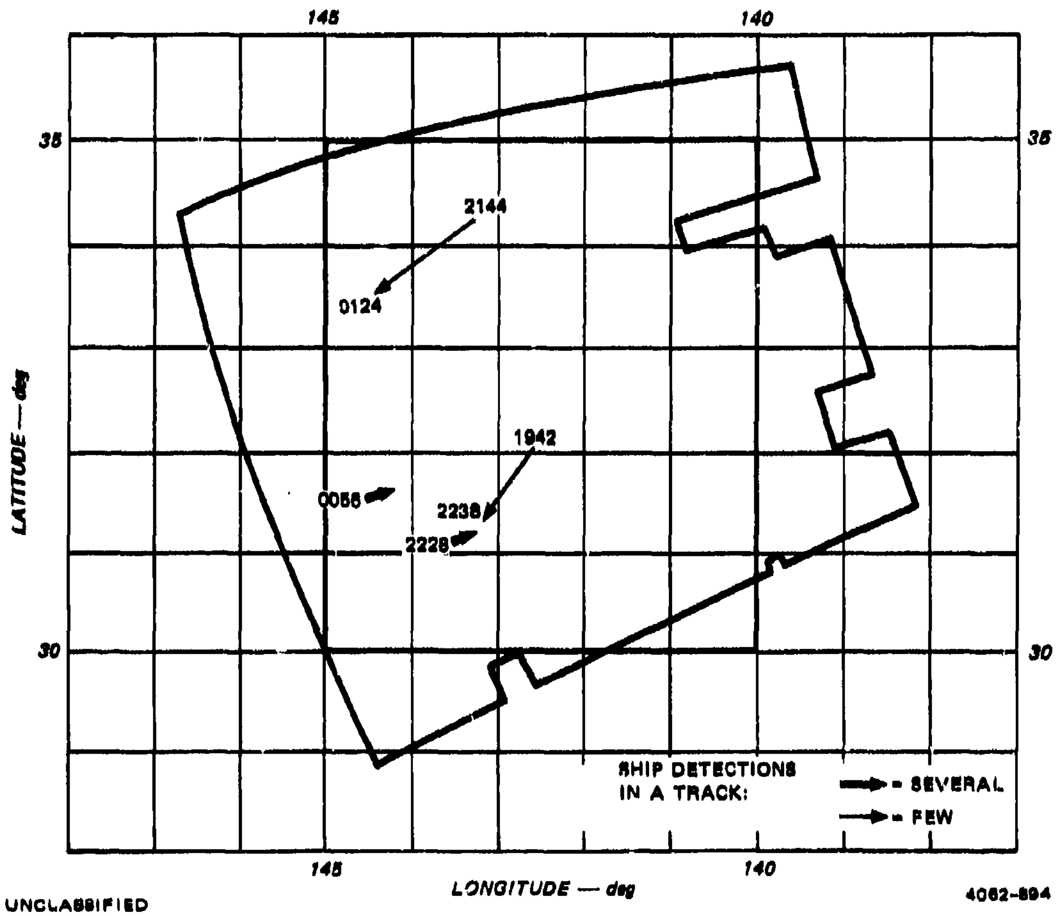

FIGURE 9 WARF OTHR SHIP TRACKS FOR 11 SEPTEMBER 1975 AND OUTLINE OF RADAR COVERAGE FROM FIGURE 3 (C)

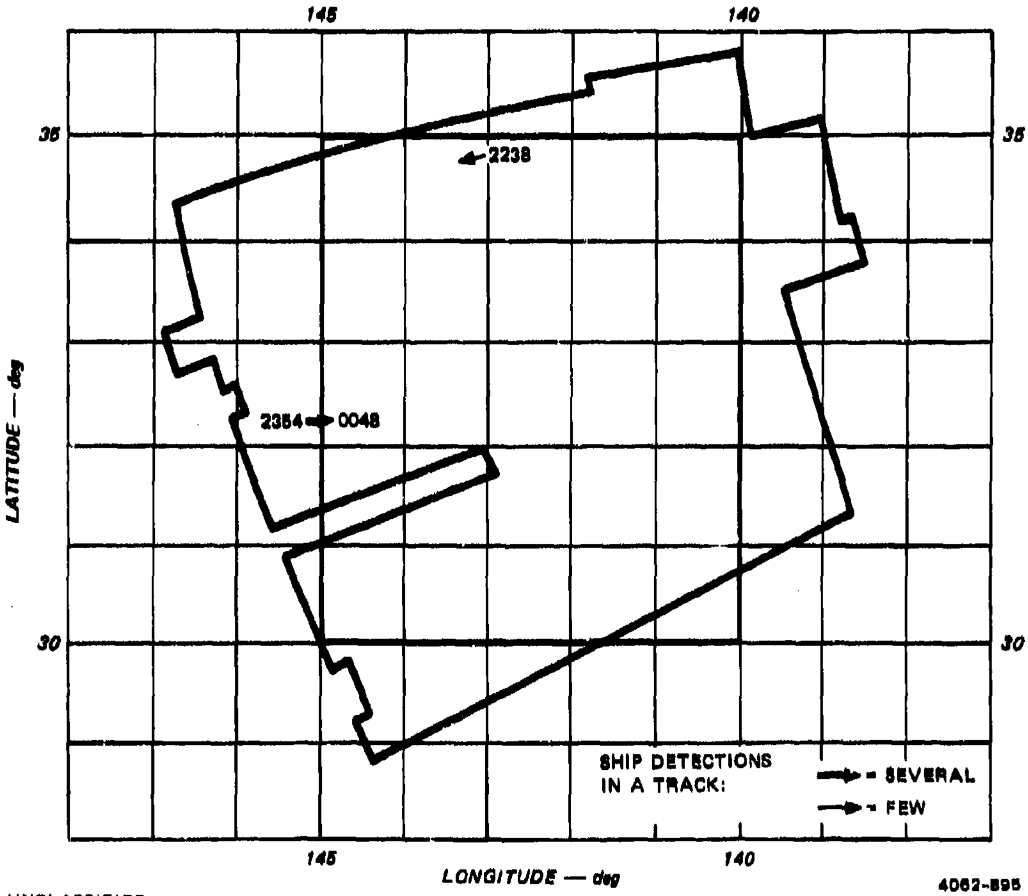

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FIGURE 10 WARF OTHR SHIP TRACKS FOR 12 SEPTEMBER 1975 AND OUTLINE OF RADAR COVERAGE FROM FIGURE 4 (C)

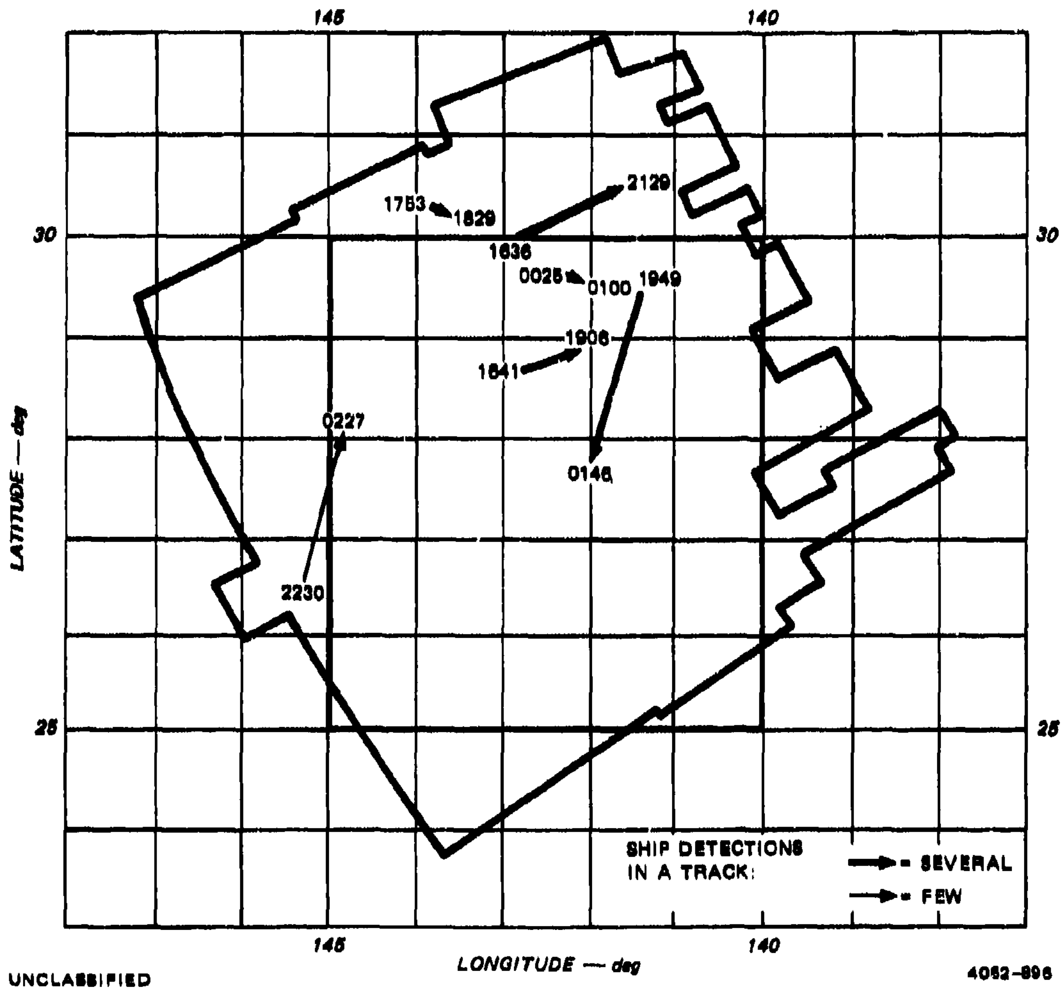

FIGURE 11 WARF OTHR SHIP TRACKS FOR 13 SEPTEMBER 1975 AND OUTLINE OF RADAR COVERAGE FROM FIGURE 5 (C)

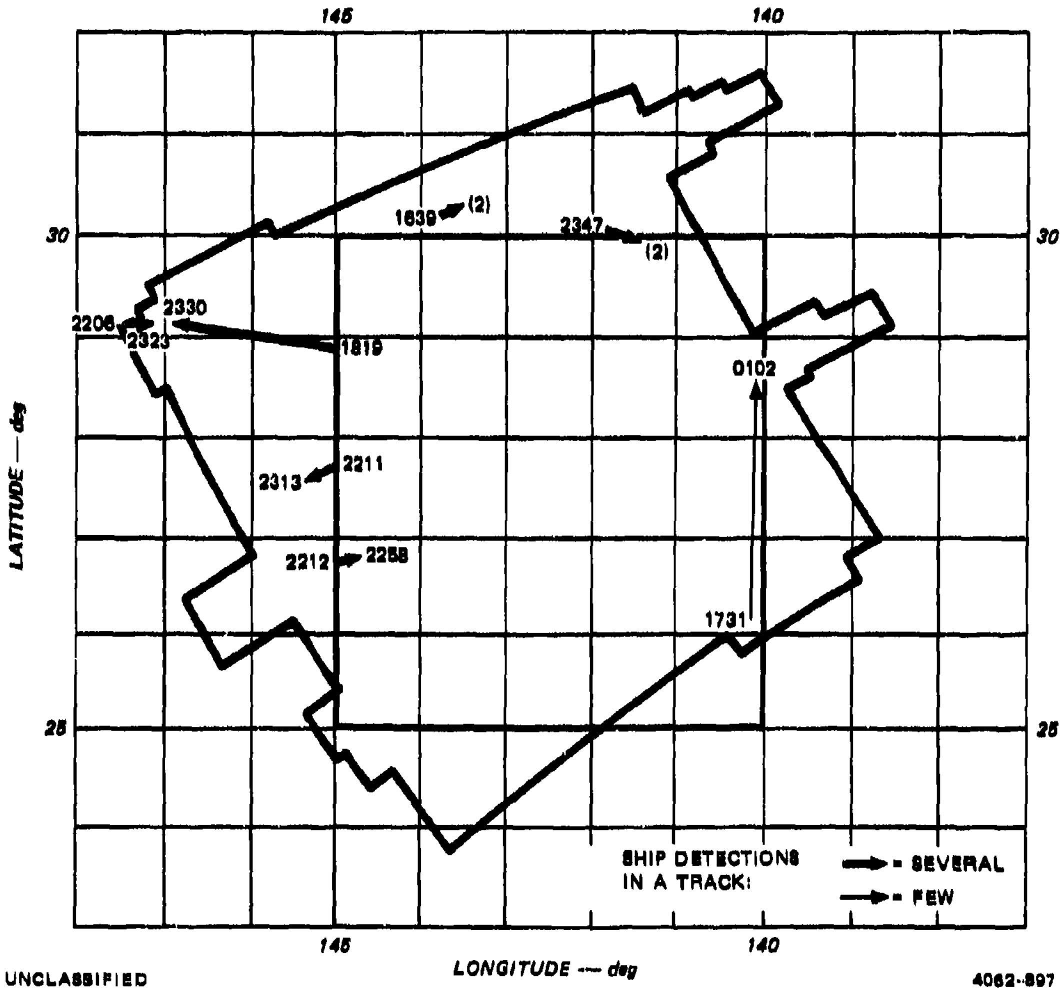

FIGURE 12 WARF OTHR SHIP TRACKS FOR 14 SEPTEMBER 1975 AND OUTLINE OF RADAR COVERAGE FROM FIGURE 6 (C)

(C)

track is plotted as either approaching or receding from the radar, depending on the Doppler shift of the target echoes. Density estimates were calculated by PSI from these distributions (Ref. 9).

(S) All tracks except for three cases were a straightforward development for a single ship. The three exceptions were the following:

(1) 10 September 1975 (Figure 8): For the track of 0100Z to 0215Z, the history of target radar coordinates was excessively spread, indicating the likelihood of two targets traveling together.

(2) 13 September 1975 (Figure 11): The track of 1636Z to 2129Z is actually the correlation of two shorter tracks for the time periods 1636Z to 1714Z and 1847Z to 2129Z. It is fairly certain that these two tracks were really the same ship.

(3) 14 September 1975 (Figure 12): Two tracks spaced by seven hours (1639Z and 2347Z to 0048Z) possessed somewhat similar radial speeds and apparent headings. These ship tracks could have been correlated with good agreement. Yet, owing to the very long time between these track segments we chose not to combine them. Additionally, the detection histories suggested the presence of two or more ships per track on each of these segments.

(S) The shipping densities calculated from WARF and P3 radar detections on 14 September aggreed almost exactly. As illustrated in Ref. 9, an attempt was also made to correlate individual P3 contacts and OTHR contacts on 14 September 1975. The original OTHR tracks were plotted on the map of P3 contacts and were extrapolated for the hours of 1700Z to 0100Z, which bracketed the times of P3 surveillance. Some additional, low-probability detections were also plotted and overlayed on the map of P3 contacts (for comparison only). While several close correlations were made between OTHR and P3 detections, there were some

(S)

high-probability OTHR ship tracks that were apparently not detected by the P3 (unless position uncertainties of 50 to 100 nmi could be assumed). There were also several P3 contacts, most notably a group of targets near the center of the area of interest (Ref. 9), that were not detected by OTHR. It is probable that small and slow ships, such as a fishing fleet, comprised this undetected group. We conclude that P3 radar and OTHR contacts should be correlated again in future experiments in order to better assess P3/OTHR target positioning.

IV CONCLUSIONS (U)

(S) The ship tracking results in Church Opal were summarized in Section I-D of this report. The ship density results derived from these measurements agreed with previous model estimates and with results from a P3 flight on the last day of WARF operation. The correlation of individual P3 contacts and OTHR ship tracks was only about half successful, however, and the reason for this unsatisfactory result is not known.

(S) With the exception of repeated OTHR tracking of Fleet units in the Outlaw Hawk experiment (Ref. 2), the number of ships tracked by WARF in Church Opal (26 total) exceeded those from any previous experiment. In addition, Church Opal was the first time that routine surveillance of large ocean areas had been undertaken.

(S) The surveillance of large areas with high spatial resolution demands careful operation strategy to ensure both high area revisit rates and efficient target hit-to-hit correlations. The real-time tracking operation in Church Opal could have been improved significantly, as follows:

(1) Possible ship detections should have been verified immediately, rather than 15 minutes or more later. This would have ensured operation on the same radar frequency, with the same ionospheric conditions, thus providing a closer match of any subsequent echo signatures to the original detections.

(2) In most cases more time should have been devoted to the detection verification process to reduce post-experiment analysis.

(S)

(3) An on-line, rapid automatic tracker would have improved target detection verification, and in particular would have saved much time in the sorting of aircraft and clutter echoes that produced false alarms. For these reasons, such a tracker is now operational for ship surveillance at WARF.

(S) The use of higher range resolution (e.g., 3 km, rather than 7.5 km) would afford increased sensitivity and accuracy and would decrease the occurrence of false alarms. Although the area coverage would be reduced, the detection of transiting ships could actually be accomplished by using one or more noncontiguous fences spaced throughout the desired coverage area (such as a 5° square). Fences spaced by 50 nmi, for example, would detect over a period of 5 hours all transiting ships with radial speeds in excess of 10 knots.

(S) The improved area scanning procedures, real-time target verification and tracking, and higher resolution, mentioned above, were demonstrated in a more recent WARF ship-surveillance test during the Church Pedal exercise led by the Naval Undersea Center, San Diego, California.

Appendix

CONSIDERATION OF SURVEILLANCE PARAMETERS AND SYSTEM PERFORMANCE (U)

Appendix

CONSIDERATION OF SURVEILLANCE PARAMETERS AND SYSTEM PERFORMANCE (U)

(S) The surveillance of wide ocean areas requires careful selection of radar operating and processing parameters. Limited processor capacity necessarily requires some sacrifice in sensitivity in order to increase the size of the coverage area.

(S) The operating and processing tradeoffs essentially fall into three categories, in order of priority:

- Target area revisit frequency
- Spatial resolution
- Integration time (both coherent and noncoherent).

The following text summarizes the effects of each of the above.

1. Tradeoff Analysis (U)

(S) Previous results (Ref. 11) illustrated the probability of detection (P_D) for ship targets assuming that the target amplitude fluctuates only as a result of polarization (faraday) rotation. The peak SNR required for detection at 90% P_D with a single, arbitrary dwell is 44 dB. This is essentially measured as the ratio of vertically polarized RCS of the ship compared to the RCS of the sea clutter. Verification of a ship detection, hence the formation of a track, requires two or more detections. Assuming only two radar looks at the target, however, a net P_D of 90% for two target hits requires a peak target SNR greatly in excess of that for only one look and a single

(S)

hit. This result follows the combinatorial probability law for the association of independent trials and events.

(S) As shown in Refs. 7 and 12, the use of more radar looks than the required number of hits dramatically reduces the required SNR for high P_D. The method of independent Bernoulli trials was used in one case to determine P_D for at least eight target hits, as a function of the number of independent radar looks at the target (Ref. 12). At the 90% P_D level, the required ship target peak SNR was 22 dB for 16 looks, 14 dB for 32 looks, and 11 dB for 128 looks. The probability of false alarm (P_{FA}) was 10^{-6} per look. The conclusion was that an enormous increase in effective sensitivity is gained by doubling the number of radar looks at a target position over the required number of detections. Other calculations show that, in general, one realizes an additional 8 dB increase in the required peak SNR by looking at a target's position a total of four times the number of required detections.

(C) The effect of increased spatial resolution is similar to that for coherent integration in the reduction of second-order sea clutter, but higher spatial resolution also reduces the coherent first-order sea-clutter amplitude and its associated Doppler processing sidelobes. The sea-clutter amplitude is reduced proportional to decreased ocean "patch" size in a range and azimuth radar cell. It thus proves very desirable to use the full WARF antenna aperture, coupled with the automatic ship detection processor that samples five contiguous beams simultaneously. The azimuth resolution at WARF is determined primarily by the fixed aperture and the radio frequency. The beamwidth is given approximately as $0.5\ (15/f_m)\ \sec\varphi$ degrees, where f_m is the radio frequency in MHz, and φ is the angle of steer up to ±32° from the boresight direction of 270° true. The range resolution is inversely proportional to the swept bandwidth, and is limited ultimately by ionospheric

(C)

dispersion. A resolution of 3 km (50-kHz bandwidth) is nearly always possible, and a 1.5-km resolution is usually possible in September. Higher range resolution also buys increased accuracy in target position measurement (with limited SNR conditions).

(S) A ship target SNR against second-order sea clutter or noise can be increased proportional to coherent integration time (3 dB per doubling) up to the limit allowed by the ionosphere. This limit is about 30 to 40 s, normally, but as much as 256 s was used effectively in one recent experiment at WARF. Likewise, the increase of noncoherent integration buys something like 2 dB per doubling of time up to ten such averages, assuming that the ionosphere does not move significantly during the averaging (or that its movement can be accounted for).

2. Final Choice of Parameters (U)

(S) The approach to Church Opal was to require, firstly, that each 5°-by-5° area be sampled at least eight times during the day's operation. This would ensure at least two detections of a ship in transit through the area with comparatively low SNR. Halving this number of looks to obtain two detections would mean the effective loss of about 8 dB of sensitivity, while the extra time, if devoted to coherent integration, would buy only 3 dB. Doubling the range resolution, to cover the same area in twice the time, similarly buys only 3 dB.

(C) The existing automatic ship detection processor (Refs. 2 and 7) utilized a 12.8-s coherent integration. Although at least twice this amount can be realized via ionospheric propagation most of the time, it could not be programmed at WARF without sacrificing Doppler coverage (which is allowable at night), or without [illegible] the automatic detection and multiple-beam processing features of the ship detection processor.

(C)
Thus, a 12.8-s coherent integration time was used for the daylight operation in Church Opal. Nineteen seconds are required for processing subsequent to the 12.8-s data sample, giving a total of 32 s processing time for a single noncoherent average.

(C) To program the transmitting-antenna beam-steering network, it was highly desirable to devote a full minute, or some integral multiple thereof, to each radar dwell. A noncoherent integration of two coherent range/Doppler maps required 45 to 50 s, thus nearly matching this criterion. A 2-dB increase in sensitivity was also thereby achieved.

(U) About 6 hours of viable operation, or 360 usable radar dwells, were expected during each day's 10-hour operation. We mean by "usable" that such dwells have sufficient sensitivity for ship detection, are uncontaminated by sources of false echoes such as meteors, and do not possess spread-spectrum sea clutter caused by ionospheric multipath.

(U) To cover an area of 5° by 5°, or about 275,000 km^2, with 360 dwells a total of eight times requires an area coverage <u>per dwell</u> of at least 6100 km^2. Each dwell consists of five antenna beams 1/4° wide that overlap by 1/4° from dwell to dwell. The equivalent coverage is therefore 1° per dwell, which amounts to 41.5 km cross-range, on the average. Thus, the range coverage per dwell needed to equal or exceed 6100/41.5 = 147 km per dwell. There are 21 individual range lines per dwell, with an overlap of 1 cell during surveillance, yielding a requirement for 7.4 km per line. This is almost exactly realized by a 50-μs (7.5-km) range resolution, and such was chosen for Church Opal.

3. Discussion (U)

(S) WARF is basically configured for high-resolution, high-sensitivity surveillance of small areas for the purpose of target

(S)

tracking and to provide a basic test bed for system improvements. Available WARF hardware must be configured for relatively low data integration time and low range resolution in order to efficiently cover a 5°-by-5° area. The range resolution could have been readily improved to 3 km (20 μs), buying 4 dB in sensitivity, but this would have reduced the coverage area to an unacceptably low size for the LRAPP density analysis.

(S) Due to environmental constraints, it is also not advisable to use range resolutions longer than 7.5 km for ship detection. In addition to further loss in sensitivity against sea clutter, much larger range increments must be processed and compared for possible point targets on each dwell. A 15-km resolution at WARF would produce 2 ms total coverage with the 20 range cells processed simultaneously. The optimum radio frequency for each of the two halves of such a coverage would often be different. At a single frequency, the signal amplitude and degree of multipath could vary significantly across the 20 range cells; under these conditions, when comparing cells for discrete echoes, the computer can sometimes choose a sea clutter component to be a target. This type of false detection has been seen at times even for the 7.5-km resolution. Most ship detection experiments have used a 3-km resolution or better with great success and a minimum of false alarms generated by clutter echoes.

(S) A modest operational OTH radar designed for ship detection would no doubt have at least the following features that only require additional off-the-shelf hardware and well-known system design techniques:

- A factor of 5 greater effective azimuth coverage (21 adjacent 1/4° beams, with a one-beam overlap during surveillance)

(S)

- A 1.5-km resolution, with a factor of 5 greater range coverage (100 range cells)
- A 30-s coherent integration and a double noncoherent average, using parallel processors to achieve a 100% duty cycle for each one-minute dwell
- Two radio frequencies simultaneously, on two transmitters and two receiving systems to double the area coverage.

The basic sensitivity achieved by this system would be no more than achievable at WARF, but the area coverage would be in excess of 50 times the area coverage of WARF: (5 in azimuth) × (5 in range) × (duty cycle factor increase) × (2 in frequencies).

(S) Assuming the coverage should be 5° by 5°, as for Church Opal, WARF must sacrifice 11 dB sensitivity compared to the operational system (7 dB in range resolution and 4 dB in coherent integration time). Additionally, however, the area coverage per unit time of the latter would have exceeded that of WARF by a factor of 10 (5 in azimuth × 2 in frequencies). An 11-dB gain in sensitivity would enable detection of much smaller ships at normal transiting speeds, and other ships over a wider range of speeds. A factor-of-10 increase in area coverage would mean efficient coverage of a 5°-by-5° area eight times in only 1 hour, or less.

(S) The WARF parameters used in Church Opal are considered sufficient to have detected ships something on the order of 400 ft or larger under normal transit through the area (radial speeds in excess of 10 knots or so), and smaller ships at slightly higher radial speeds.

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Date: Undated
Available at Applied Research Laboratory, U of Texas (ARL:UT) (55327)

Title: CHURCH OPAL DATA ANALYSIS PLAN
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Title: CHURCH OPAL DATA EXTRACTION FORMAT DESCRIPTIONS
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Title: CHURCH OPAL AND CHURCH ANCHOR EXERCISE: DATA FROM BOTTOM ARRAYS
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Author: Hecht, R. J.
Originator: Underwater Systems Inc.
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Ref. No.: NOSC TR394
Date: October 1978
Available at MC/NAVOCEANO (85007295)

Title: OTH RADAR SURVEILLANCE AT WARF DURING THE LRAPP CHURCH OPAL EXERCISE
Formerly SECRET
DTIC No.: AD CO10 483
Author: Barnum, J. R.
MCS No.: 85010085
Originator: Stanford Research Institute
Ref. No.: TR39S231
Date: March 1977
Available at MC/NAVOCEANO (85010085) and NRL (528986)

Title: CHURCH OPAL Exercise Summary, 1 September 1975 - Xonics, Inc
Formerly CONFIDENTIAL
DTIC No.: AD C004 343
Available at NRL (516165), ARL:UT (??) and MC/NAVOCEANO (??)

Title: CHURCH OPAL EXERCISE PLAN
Formerly SECRET
Author: none
Originator: Xonics, Inc and Office of Naval Research
Ref No: Xonics 1101
Date: August 1975
Available at NRL (521309), ARL:UT (55397) and MC/NAVOCEANO (??)